Estimation of carbon balance components over agricultural lanscapes based on remote sensing and field measurements

Thesis of PhD Dissertation

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Introduction and objectives

Biogeochemical cycles in general and the biosphere-atmosphere carbon exchange in particular are of current high priority research areas for the understanding of climate change. Uncertainties in future climate scenarios need a more accurate incorporation of biosphere-atmosphere interactions because of the two-way interaction between the carbon cycle and the climate system. Oceans and the terrestrial ecosystems currently act as a net sink of atmospheric CO_2 partly compensating for anthropogenic emissions. One of the most important scientific questions is whether this sink capacity can be maintained or even increased under changing environmental conditions.

Remote sensing applications provide spatially explicit information on land surface (including vegetation state and activity), representing a valuable source of measurement based data for carbon cycle modeling. In my PhD research I am dealing with the possible applications of satellite remote sensing in estimating vegetation-atmosphere CO_2 exchange using a data-oriented model focusing especially on agroecosystems. Based on remote sensing data it is possible to estimate the gross carbon uptake of plants (Gross Primary Production; GPP) which is one of the most important and highly uncertain carbon cycle components of terrestrial ecosystems. The two main objectives of the dissertation are (i) to investigate the accuracy of remotely sensed GPP estimations against *in situ* measurements carried out over Hungarian and international agricultural fields and (ii) to improve model accuracy based on model parameter optimization.

Data and methods

The MOD17A2 product that is built upon data provided by the MODIS[1] sensor onboard NASA's[2] *Terra* and *Aqua* satellites provides *Net Photosynthesis and GPP* data since 2000 with 1 km spatial, and 8 days temporal resolution. The underlying MOD17 model is based on the LUE[3] approach and requires weather data to simulate environmental stress on plant functioning. The 5-parameter model considers minimum temperature (T_{min}) and atmospheric vapour pressure deficit (VPD) data to reduce maximum LUE (ε_{max}) of the plant according to the actual environmental circumstances. GPP data is calculated in the model based on other MODIS data products that describe land cover information and vegetation activity.

Evaluation of remote sensing GPP estimations is usually carried out using field measurements of GPP as validation and calibration dataset. Application of GPP data from eddy covariance (EC) measurements is a common and frequently applied way to assess gross carbon uptake based on field measurements on the plot level. The actual representativeness of the EC measurements is influenced by several factors, such as measurement height (h), wind direction, atmospheric stability, orography, etc. The so-called footprint, or source area of the EC tower gives the area from which the measured CO_2 flux originates. Its location varies with time depending on atmospheric circumstances, but when integrated over a longer time period it provides information

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[1] MODerate Resolution Imaging Sectroradiometer
[2] National Aeronautics and Space Administration
[3] Light Use Efficiency

on the contribution of the neighboring areas to the measured flux. In general, the extent of the footprint is greater in case of a taller tower (relative to the canopy height).

In my PhD work, I used two types of EC data: data from a tall tower in Hungary and data from selected members of a network of short-tower based EC sites (FLUXNET) across Europe and the US.

In Hungary (near Hegyhátsál, Vas county) continuous measurements of carbon dioxide fluxes with eddy-covariance method have been taking place since 1997 at 82 m height (FLUXNET site ID: HU-He1). Being a tall tower, HU-He1 provides regional scale information on the surrounding heterogeneous agricultural landscape, hence it is expected that representativeness of the data is closer to the 1 km size of the MODIS pixel then in case of a shorter tower. 6 measurement years was used in the study to explore the effect of landscape heterogeneity on validation.

For calibration of MOD17 short-tower ($h<30$ m above the canopy) based EC tower sites have been selected over croplands providing nearly 60 site-years of GPP data. C3 and C4 type cereals are grown on the study sites. After standardized data processing, I used this dataset to perform multi-site validation and calibration of the MOD17 model.

Results

The main results of the PhD work are as follows:

1. A coherent and standardized database of GPP data from agricultural EC validation sites was built. Four different methods were implemented to fill data gaps in EC measurements and to retrieve GPP data. Based on the four estimates of GPP, uncertainty of GPP data was assessed. The database also contains ancillary data such as meteorological measurements and crop information in standardized format. The database is also suitable for future validation/calibration of other ecosystem models.
2. Adaptation of the MOD17 model was carried out to be able to modify model setup and model parameters.
3. The first validation of the MOD17 model for Hungarian agricultural landscape has been performed, also considering the special properties of the site. The validation included four steps in four model setups: (i) the original model setup (ii) setup to account for errors of the input data (iii) setup for the rough consideration of tower footprint over the heterogeneous landscape, (iv) downscaling of the model using 250 m resolution NDVI data combined with footprint information. The results suggested underestimation of cropland validation data by original MOD17 estimates.
4. It was shown that, patchiness of the vegetation in the footprint considerably affects validation results, which means that mismatch of spatial representativeness of remote sensing and *in situ* data need to be accounted for. However, the dynamic consideration of temporal

changes of the footprint combined with a downscaling of the model to the approximate spatial scale of the individual crop fields in the region improved model-measurement agreement. Due to downscaling modeling efficiency (ME) increased from 0.783 to 0.884, root mean square error (RMSE) decreased from 1.095 gC m^{-2} day^{-1} to 0.815 gC m^{-2} day^{-1}, although GPP remained underestimated (bias decreased from −0.680 gC m^{-2} day^{-1} to −0.426 gC m^{-2} day^{-1}). This suggests that spatial mismatch is not solely responsible for the disagreement.

5. A multi-site validation of the MOD17 model has been carried out over croplands. The results showed a significant underestimation of measured (EC) data. The underestimation was more pronounced in case of C4 than C3 plant types. This raises the need for a crop specific separation of the current single general crop type in the MOD17 model. To our knowledge, such an extensive, multi-site evaluation of the model over agricultural vegetation has not been reported in the scientific literature so far.
6. Sensitivity analysis and model calibration of MOD17 was carried out using the GLUE[4] method, which is a Monte-Carlo based global optimization approach. The model turned out to be most sensitive to the ε_{max} parameter while other parameters (describing T_{min} and VPD stress) barely influence model result.
7. The optimized parameter sets, obtained via a crop specific calibration of the MOD17 model for C4 and C3 plants separately, resulted in

[4] Generalized Likelihood Uncertainty Estimation

higher ε_{max} for C4 than for C3 crops (0.002527 kg C MJ^{-1} 0.001487 kg C MJ^{-1}, respectively). The validation of the optimized MOD17 model for C4 and C3 plants separately resulted in a much better agreement between remote sensing and EC tower based estimates (R^2 = 0.356 (p=0.001) and 0.71 ($p \leq 10^{-7}$)).

Conclusions

The first validation results of the MOD17 model for Hungarian croplands revealed that an appropriate methodology is required in order to obtain defensible validation results at regional scale. The results demonstrate that careful application of remote sensing based information can provide reasonable estimate on cropland GPP for both C3 and C4 plants, especially if consideration of differences between – at least – basic physiological properties of crops is introduced in the model. Due to the multi-site approach, the results can contribute to a more effective use of the MOD17 remote sensing product for croplands over large regions of the USA and Europe. Croplands occupy about 45 % of the European and 18 % (35% together with pastures and rangeland) of the USA land surface, clearly reflecting their significance in the continental carbon balance.

In Hungary, availability of reliable data on the spatial distribution of C3 and C4 crops, however, can limit applicability of the crop-specific approach described above. Therefore, data collection and the application of remote sensing data at the appropriate spatial scale is an important and challenging task in the future to support Hungarian carbon balance estimations.

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